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The mechanism of learning spatial locations relative to boundary: an MSc study

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Abstract

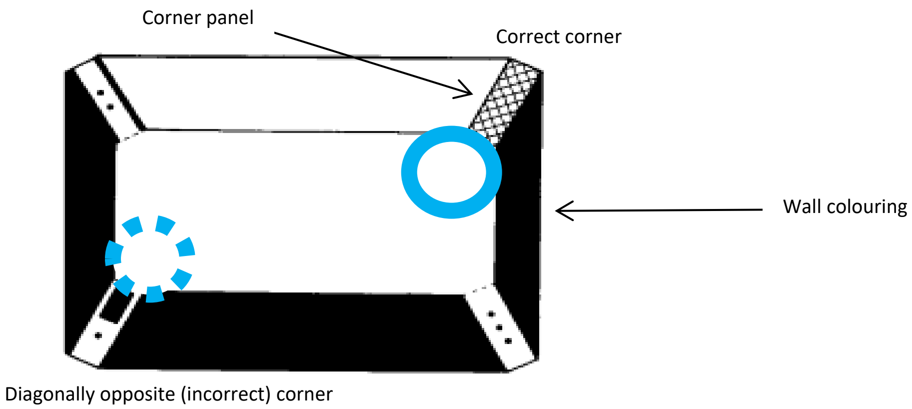
Spatial learning is a crucial aspect of daily life. However, there is ongoing debate as to whether the cognitive mechanism of learning locations relative to spatial boundary is qualitatively different from learning locations in reference to discrete non-geometric features. To investigate this, a non-immersive virtual reality (VR) protocol was employed. In a novel VR task, spatial boundary was shaped as an irregular polygon and salience of its segments was manipulated. Using a repeated measures design, participants (n=39) had to accurately learn locations in reference to a boundary with: i) a salient segment proximate to the target location; ii) a salient segment remote from the target location; or iii) no salient segments. The learning accuracy was compared across conditions to reveal whether participants relied on the discrete segments (non-geometric features) of boundaries or the overall geometric shapes of these boundaries to reference target locations. Participants' conscious learning strategies were also analysed. It was observed that the accuracy of learning locations relative to a complex and unfamiliar boundary improved with increased salience of one of its segments, irrespective of the conscious learning strategies used. This data, as well as mixed findings from other studies, are explained in the context of Cognitive Load Theory and suggests that the propensity to use overall geometric shape of a boundary for location learning varies as a function of the complexity and familiarity of that shape.

Introduction

Human ability to comprehend and make use of physical space (spatial learning) is central to many basic, social, and industrial functions. Since the introduction of Cognitive Map Theory (Tolman, 1948), researchers uphold the notion that humans, as well as animals, remember their spatial environment by forming map-like representations. Such cognitive maps integrate previously visited locations and encountered environmental cues into a unified construct, which facilitates flexible navigation and spatial problem solving. Cues used for learning spatial locations are divided into two categories: (1) discrete objects or features, referred to as 'landmarks'; and (2) extended surface structures, denoted as 'boundaries' (Lee, 2017). Depending on task demands, both types of cues could be used for location learning: a location could be learned in reference to landmarks; equally, the location could be learned in reference to boundary demarcations (Lew, 2011).

Some researchers assert that learning locations in reference to spatial boundary (boundary-learning) involves a qualitatively different mechanism to learning locations in reference to landmarks (landmark-learning). Many refer to the existence of a 'geometric module' in the brain, which is thought to instantaneously process geometric information of space (Cheng, 1986; Wang & Spelke, 2003; Chiandetti & Vallortigara, 2008). Cheng (1986) initially proposed this notion to explain findings from a series of location learning experiments with rats. He used a rectangular enclosure with differently coloured walls. A distinct panel (landmark) was placed in each corner of the enclosure. Rats were taught to find food by digging beneath the bedding of one of the enclosure corners. That corner was distinguished by unique landmarks (i.e. distinct panel and colour of the walls), whilst being geometrically identical to the diagonally opposite corner of the rectangular enclosure (Figure 1). At test, rats were placed into the same enclosure, but the food was removed from it. Location of their initial dig in search for the food was recorded. Rats were found to express equally significant preference for the correct as well as the diagonally opposite (incorrect) corners.

Figure 1. Cheng (1986): schematic representation of the enclosure



The incidence of such rotational errors indicated that rats prioritised overall geometry of the enclosure to learn locations and ignored distinguishable (salient) landmarks. Cheng (1986) thus concluded that, although locations could be successfully learned via both cue types, boundary cues, if available, were given priority over landmarks. He proposed that there was either a separate geometric storage module in the brain, or different rules for easy access to the geometric information stored in memory.

Since this initial research, the existence of a 'geometric module' has gained further empirical support in both animal (i.e. domestic chicks, fish, mice, monkeys) and human research, using analogous experimental paradigms (Benhamou & Poucet, 1998; Pearce et al., 2001; Wang & Spelke,

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2003; Cheng & Newcombe, 2005; Chiandetti & Vallortigara, 2008; Lee & Spelke, 2010; Lee et al., 2013). Neuroimaging studies have further demonstrated differential neural networks for boundary and landmark-learning, which was assumed to evidence the modularity of spatial processing (Sutton et al., 2010; Doeller et al., 2008).

Giving further support to the notion that landmark and boundary learning are two qualitatively different cognitive mechanisms, Doeller and Burgess (2008) specified that boundary cues were processed incidentally, and were not in equal competition with landmarks for limited attentional resources. They concluded this, as in their VR experiments with humans they failed to observe blocking and overshadowing of boundary cues by landmarks. That observation was contrary to the standard associative learning model (Rescorla & Wagner, 1972). According to the associative model, blocking takes place when learning relative to one cue fails to take place if the other cue already accurately predicts the desired outcome. Overshadowing occurs during concurrent learning to several cues (compound condition), where strength of association to each of these cues is reduced, compared to learning in reference to each cue separately (simple condition). To expand, participants failed to reference locations to landmarks after learning these locations relative to a circular boundary in preceding trials (i.e. landmarks were blocked by boundary). However, participants managed to re-learn locations relative to boundary, even after learning these locations to landmarks, and without explicit instruction to do so (i.e. landmarks failed to block boundary). Similarly, in compound condition boundary cues overshadowed landmarks, but landmarks failed to overshadow boundary. Thus suggesting that these cues are, at some level, qualitatively different, and that boundary cue learning takes precedence.

Nonetheless, research is not unequivocal with further (more recent) studies demonstrating that boundary cues do not always take precedence over landmarks in location learning (Gouteux et al., 2001; Learmonth et al., 2002; Cheng, 2008; Lew, 2011; Sturz et al., 2012; Zhou & Mou, 2016). In some cases boundary cues compete with non-geometric cues for attentional resources (Gray et al., 2005; Pearce et al., 2006), while in others, non-geometric cues actually improve the accuracy of boundary-learning (Graham et al., 2006; Pearce et al., 2006).

For instance, Redhead et al. (2013) asserted that the shape of a boundary may influence the role that non-geometric cues play in location learning. They recruited human participants and used a non-immersive VR environment to replicate a common location-learning paradigm employed in animal research. In the course of three experiments, participants (n=82) were placed into a virtual pool of water and asked to find a submerged invisible platform in one of the corners by swimming to it. For half of the participants a small floating beacon (landmark) marked the location of the platform in the pool. In that condition both the landmark and the boundary could be used to learn the target location

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(compound condition). For the remainder of the participants there were not any landmarks in the pool – only the shape of the swimming pool (boundary shape) could be used to reference the target location (simple condition). There were two types of swimming pools in the experiment: one was shaped as a triangle, and the other as a trapeze. The attributes of boundaries forming both pools were closely matched. They were equally sized, and individual walls of each boundary could not be easily distinguished from one another. The difference between the boundaries was the number of wall segments and the overall geometric shape. At test, the platform and the landmark were removed from the pools. The latency to reach the target location and the search time spent in that location were measured. As in the study by Doeller and Burgess (2008), the effectiveness of learning in compound and simple conditions was compared. Redhead et al. (2013) found that learning to boundary in the trapeze-shaped pool was significantly more accurate in the simple than in the compound learning condition. For the triangular pool, there were no differences between conditions. Redhead et al. (2013) determined that the trapeze boundary shape got overshadowed by the landmark, whereas, the triangular shape was given processing priority. They thus concluded that neither 'geometric module', nor the standard associative rules fully explained cue competition within the spatial domain, proposing that certain characteristics of boundary shapes might have some influence over the choice of learning cues.

Given such a wide disparity of research findings, it is possible that there is more than one factor at play in determining whether boundary cues are prioritised in location learning (Gouteux et al, 2001; Learmonth et al., 2002; Cheng & Newcombe, 2005; Cheng, 2008; Lew, 2011). Research into human cognitive processing strategies suggests that prioritisation of certain cues over others is largely determined by the interaction of cue characteristics with the processing capacity of the perceiver (Pachur & Bröder, 2013). To clarify, cues that require less processing effort are prioritised over cues that are associated with higher processing costs. The processing effort, according to Cognitive Load Theory, is determined by the limitations of working memory (WM), a temporary store for information, which holds information just long enough to perform a certain task (Sweller, 1988; 1994). In the spatial domain, people generally process no more than four spatial orientations or four visual objects, defined by the conjunction of four features in WM, at one time (Luck & Vogel, 1997; Vogel et al., 2001). Thus a complex boundary shape, comprised of four or more walls that come together at oblique angles, is likely to overload processing capacity, and is unlikely to be prioritised over non-geometric cues; while a boundary formed by three walls (e.g. a triangle) could be given priority over landmarks.

However, within Cognitive Load Theory it is also suggested that WM limitations can be compensated for by long-term memory (LTM) (Sweller, 1988; 1994). The latter enables storage of

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numerous informational elements over a long period of time in an interconnected and highly organised structure, progressively generated through learning. Each organisational unit within LTM, denoted as 'schema', "consolidates the elements of information according to the manner with which they will be dealt" (Sweller, 1994, p. 296). For example, the schema associated with four equally sized lines and four straight angles may be 'a square'. Four lines and four angles represent eight units of information, while the associated schema ('a square') could be processed as a single unit. Therefore, despite their multi-component structure, schemas for geometric shapes might get automatically accessed and managed as single visual objects by WM, reducing processing demands. Thus, provided that there is a representation for the encountered shape in LTM, even a complex boundary shape could be used for location learning without exceeding the processing capacity of the perceiver.

Arguably, the above could explain the findings of Cheng (1986) and Doeller and Burgess (2008). Cheng (1986), as well as many other researchers supporting the 'geometric module' concept, used rectangular enclosures in their experiments, while Doeller and Burgess (2008) used a circular boundary. Both shapes are frequently encountered in day-to-day navigation and their representations are likely to be stored in LTM. Participants in the Redhead et al. (2013) study might have failed to prioritise information provided by the trapeze boundary over landmarks due to the inability to easily match it to any existing schema in LTM and their inability to quickly form a new representation for such a complex shape in WM. Contrasted with this, the triangular pool shape may have been both simpler to process and more familiar, leading to it being prioritised over landmarks.

Building on this logic, if processing of the boundary as a single unit is subject to schema availability, then novelty (e.g. a shape not encountered in day-to-day navigation) and complexity (e.g. more than four component parts) of a boundary may prevent its geometric shape from being processed as a single unit. Here instead, non-geometric cues would be utilised for location learning. For example, high salience of one boundary segment (e.g. a wall) in such cases could improve accuracy (Kalyuga et al., 1999).

There is also the possibility that proximity of the salient segment to the target location interacts with cognitive load. To expand, if a target location and a salient segment cannot be seen in the same view frame, additional cognitive processing would be required to integrate their representations into WM (Tarmizi & Sweller, 1988; Sweller et al., 1990). Alternatively, perceiving the target location and salient segment in the same view frame could minimise the cognitive load and maximise accuracy.

However, it can be further argued that if boundary shape is processed via a specialised 'geometric module', then the novelty and complexity of a shape will not prevent it from being perceived as a single unit. Therefore, in this case, the salience of a boundary segment and its proximity to the target location would be irrelevant, and not affect the accuracy of learning.

Finally, according to Kato and Takeuchi (2003), an additional contributing factor that might need to be taken into account when considering spatial location learning is the consciously chosen learning strategy. In their research they observed that people who report flexibly using both geometric and non-geometric information for learning locations are generally more accurate than those who adhere to the exclusive use of either one of these cues. Thus in any research, this aspect (i.e. verbal report) should be investigated.

In sum, in respect to the above theory and research the present investigation set out to (1) determine whether locations are learned in reference to salient segments, rather than the overall shape of a novel and complex boundary; as well as to explore (2) whether proximity of the salient segment reduces cognitive load during boundary-learning; and (3) whether conscious use of flexible learning strategies improves boundary-learning.

Methods

Participants

This research was designed and conducted in accordance with the Code of Human Research Ethics (The British Psychological Society, 2014) and approved by the local departmental ethics committee.

Seventy participants were recruited online using the 'University of Derby Psychology Research Participation System' and 'Call for Participants' platform. Only participants aged 18 and over, fluent in the English language and without any severe visual impairments (e.g. visual agnosia, simultagnosia, visual neglect) could take part in the research. No payment was offered in exchange for participation. However participants were given points which enabled them to advertise their own research on the same system. Data obtained from participants who did not complete the experiment or did not fully comply with the procedure was excluded from analyses, resulting in a total of 39 participants. These were 29 females (age M=25; SD=8.1; range 18-49) and 10 males (age M=24.7; SD=9.1; range 18-46), with an overall mean age of 25 years (SD=8.3; range 18-49).

Materials

Eighteen sets of videos showing navigation in non-immersive 3D VR environments were created using UnrealEngine4 software. Each set contained one 'learning' and one 'test' video, as described below. Each video lasted 45 seconds. The environments were comprised of a finite plane limited by

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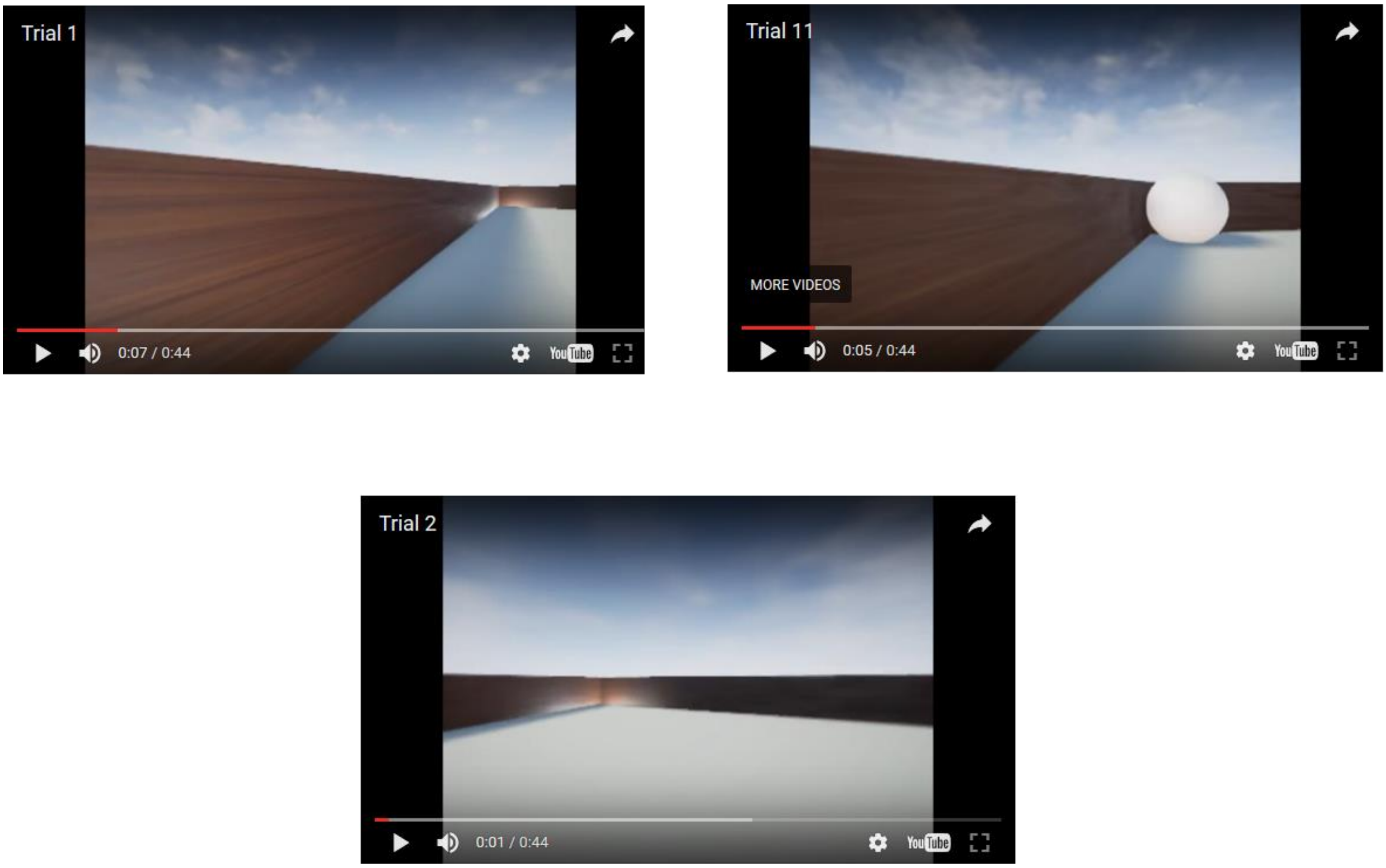
five boundary walls, forming an irregular polygon, and the sky projected at infinity. The exact shapes of the polygons differed between trial sets.

Learning Trials: Learning videos [https://youtu.be/S_aguBCOXfM] showed first-person perspective navigation along the whole length of the boundary and 360 degree rotation in the centre of the arena in a clockwise direction. A white ball (target object) was placed in one corner of the arena (Figures 2 & 5).

Figure 2. Learning trials



Test Trials: Test trials [https://youtu.be/L6IMjy8c35s] were the same as learning trials, with the exception that the direction of navigation was counter-clockwise. Also the target object (white ball) was removed, and every corner of the boundary was marked with a letter (i.e. A, B, C, D, E) (Figures 3 & 5).

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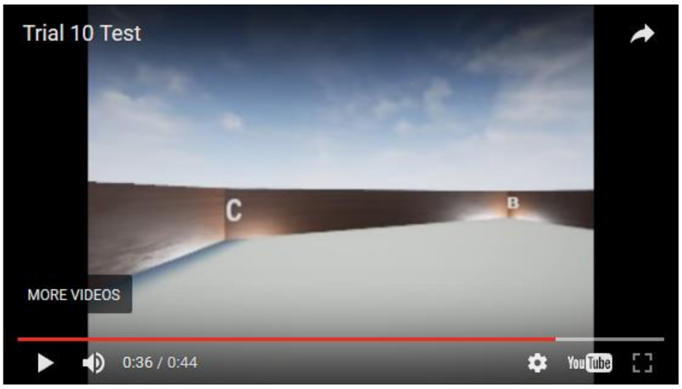
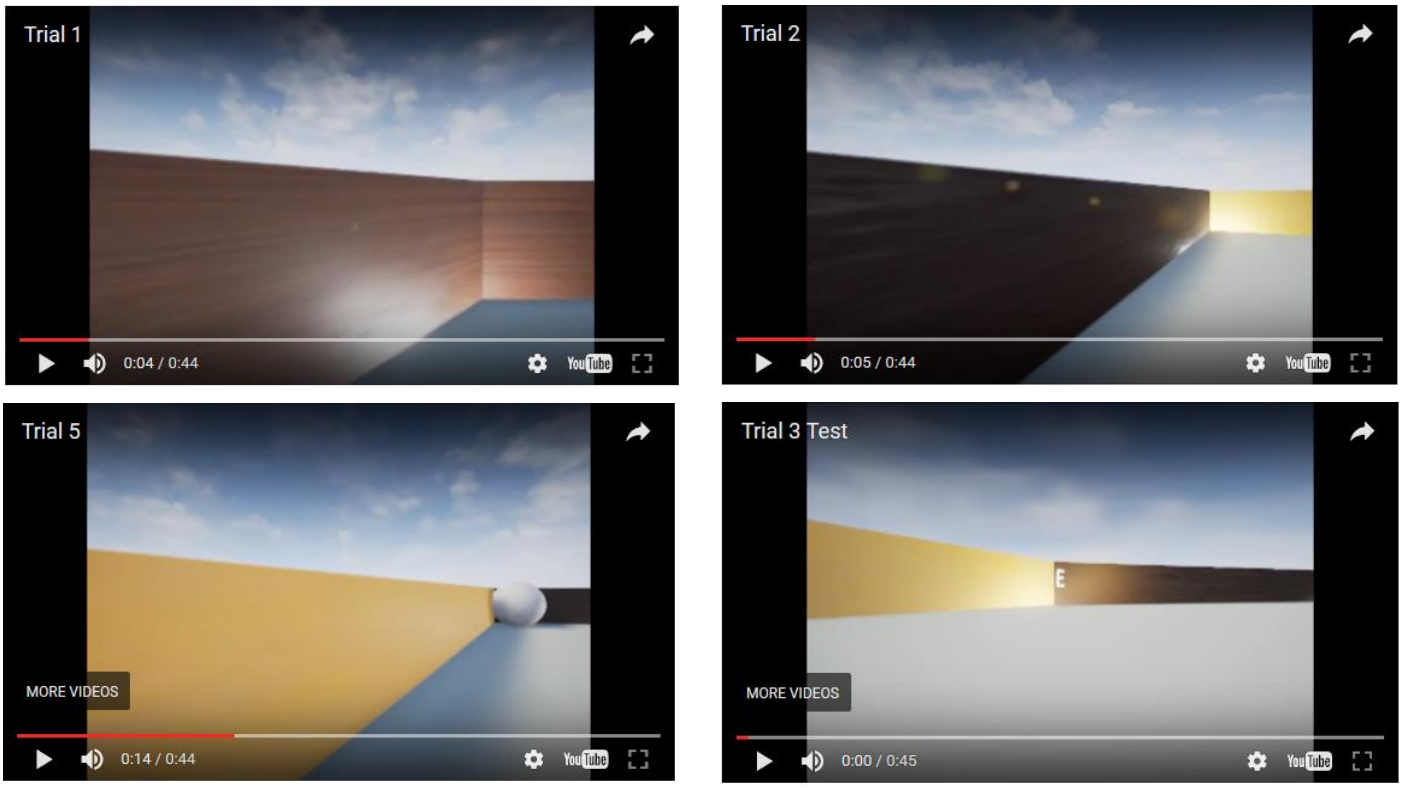
Figure 3. Test trials



Importantly, the colouring of boundary walls varied between trial sets to distinguish three conditions: (1) all five boundary walls were the same brown colour – ‘geometry’ condition; (2) four boundary walls were brown and one wall adjacent to the target object was yellow – ‘local’ condition; (3) four walls were brown and one wall remote from the target object was yellow – ‘remote’ condition (Figures 4 and 5).

Figure 4. The colouring of boundary walls



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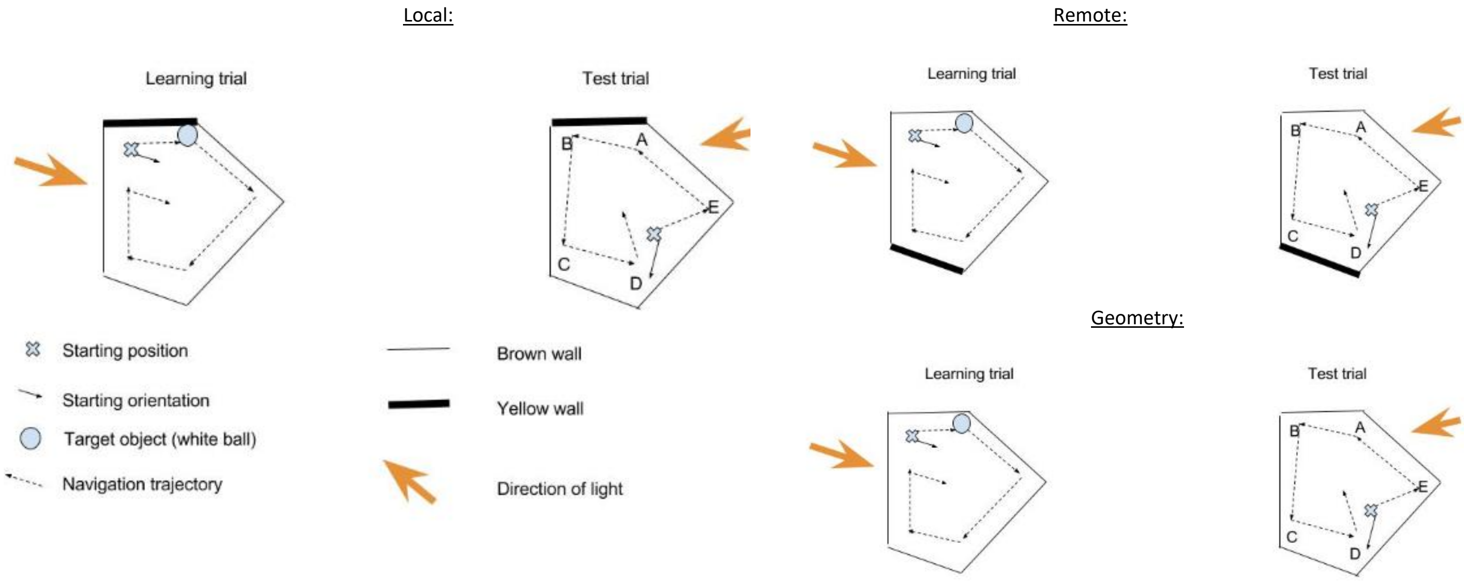
Procedure

The experiment was set up and conducted online via the Qualtrics platform ("Qualtrics", 2017). The videos were uploaded on YouTube and embedded into the Qualtrics survey. Participants used their own workstations, computers and internet connection, while being instructed to find a quiet work space. Following informed consent, two practice trials preceded the experiment.

The experiment proper consisted of 18 trial sets. In overview, in a given trial set participants began by watching the learning video. Their task was to remember the location of the white ball (Appendix 1). They were then presented with the 'test' video and asked to identify the corner in which the white ball was located in the learning video. Participants entered the corresponding letter in the appropriate field on the screen and described their learning strategy (Appendix 2).

Each condition comprised 6 trial sets. All trial sets were randomly intermixed in the experiment. Thus all participants completed all three conditions (Figure 5). Half-way through the experiment (i.e. after nine trial sets), participants were given a five-minute break. At the end of the experiment, participants were asked to define the strategy that they used for location learning throughout the experiment. Their age and gender were also recorded (Appendix 2). On average the experiment lasted around 40-50 minutes. Upon completion, participants were presented with debriefing information.

Figure 5. Schematic representation of conditions



Measurement

Participants' accuracy scores were represented by the number of correct responses in each condition. To determine participants' conscious learning strategies, their responses to the relevant questions were

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categorised as: learning in reference to a salient segment of the boundary that was close to the target location (Local); learning in reference to a salient segment of the boundary that was remote form the target location (Remote); learning in reference to the overall shape of the boundary (Geometry); or using a combination of several strategies (Flexible).

Findings

The mean percentage of correct responses across conditions was 70% (M=12.6, SD=3.2). A 3x3x2 mixed measures ANOVA analysis of the scores was conducted with a within-subjects factor of 'condition' (local/remote/geometry), and two between-subjects factors of 'conscious learning strategy'(Local/Remote/Flexible) and 'completion time' (20-39 min - 'short'/40-100 min - 'expected'), controlling for 'accuracy category' (0-6 'low'/7-12 'medium'/13-18 'high'). Completion time was included in the analysis to ensure that it did not affect the distribution of scores across conditions. Additionally, overall accuracy was controlled for, as it was observed that total scores for each participant ranged between 3 and 17 (M=12.7; SD=3.2). Such a wide score range could potentially skew the actual pattern of score distributions across conditions.

There was a significant main effect of condition $F(2,31)=10.6$, $p<0.001$, $\eta p2=0.25$. Pairwise comparisons revealed that participants' performance in the 'local' (M=5.3, SD=1.2) and 'remote' (M=4.9, SD=1.3) conditions was equivalent ($p=0.211$), but in both cases more accurate than in the 'geometry' (M=2.5, SD=1.6) condition (local: $p<0.001$; schematic: $p<0.001$) (Figure 6).

In respect to learning strategy, none of the participants reported using the Geometry strategy (0%), whereas 35.9% reported using the Local strategy, 53.8% the Remote strategy and 10.3% the Flexible strategy. However, neither the effect of 'conscious learning strategy' $F(2)=1.5$, $p=0.23$, $\eta p2=0.9$ nor the interaction between 'condition' and 'conscious learning strategy' $F(4,64)=0.66$, $p=0.62$ $\eta p2=0.4$ reached significance.

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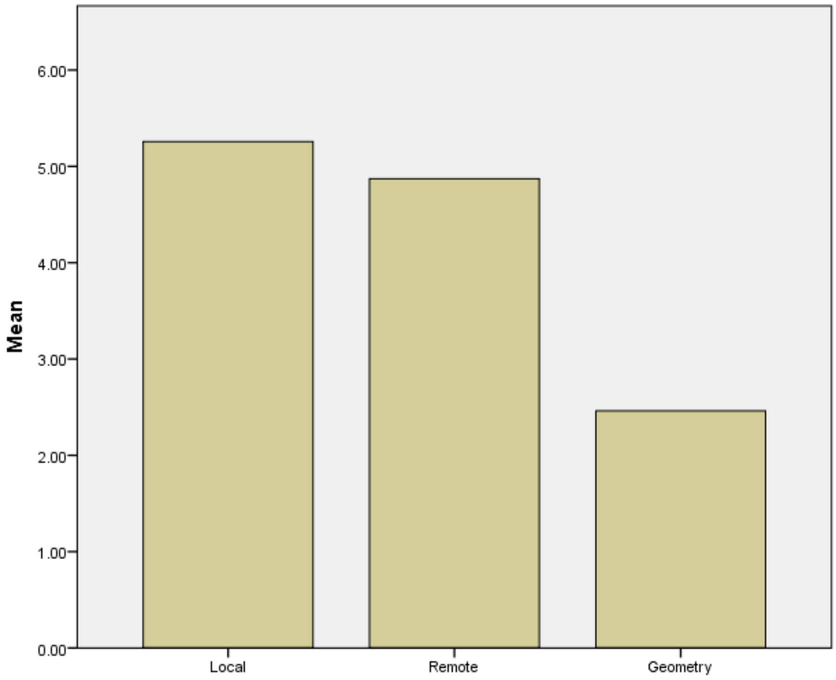
Figure 6. Mean accuracy score in local, remote and geometry conditions



Additionally, whilst there was no main effect of 'completion time' $F(1)=0.02$, $p=0.88$, $\eta p2=0.001$, the interaction between 'condition' and 'completion time' was significant $F(2,31)=4.99$, $p=0.01$ $\eta p2=0.14$. However, post-hoc analyses revealed that the pattern of score distribution across conditions was not impacted by 'completion time':

(i) Participants who completed the experiment in shorter timescales demonstrated a trend towards greater accuracy in the 'local' (M=5.6, SE=0.25) and 'remote' (M=4.6, SE=0.29) conditions $t(13)=2.46$, $p=0.03$ (significance was acknowledged with $p<0.025$ for that analysis), as compared to the 'geometry' (M=1.96, SE=0.33) condition ('local' $t(13)=12.2$, $p<0.001$; 'remote' $t(13)=7.35$, $p<0.001$).

(ii) Participants who completed the experiment in the expected timescales, were also equivalently accurate in the 'local' (M=4.6, SE=0.23) and 'remote' (M=4.64, SE=0.27) conditions $t(24)=0.11$, $p=0.91$, whilst being less accurate in the 'geometry' (M=2.82, SE=0.3) condition (local: $t(24)=7.67$, $p<0.001$; remote: $t(24)=5.53$, $p<0.001$).

Finally, there was no three-way interaction between the 'condition', 'strategy' and 'completion time' variables $F(4,64)=0.81$, $p=0.52$, $\eta p2=0.05$.

In supplementary analyses, a partial correlation was run to determine the relationship between the order of trials and accuracy scores for each trial, controlling for 'condition'. It demonstrated that there was no correlation between these factors $r(15)=-0.1$, $p=0.7$.

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Discussion

To investigate whether Cognitive Load Theory (Sweller, 1988; 1994) could be applied to the mechanism of boundary-learning, a VR experiment was conducted. It tested participants' reliance on non-geometric cues (salient boundary walls) when learning locations in reference to a complex and novel boundary shape. The salience of boundary walls was manipulated across conditions and the respective accuracy scores were compared. Participants were expected to be significantly more accurate in the conditions where one boundary wall could be easily distinguished from other walls ('local' and 'remote'), as opposed to the condition where all boundary walls looked similar ('geometry'). Additionally, participants were asked to define their conscious learning strategies in a bid to investigate whether the use of a flexible conscious learning strategy would result in high accuracy across conditions. In respect to these aims, the main findings were that participants were more accurate in learning locations in the 'local' and the 'remote' conditions than in the 'geometry' condition. However, accuracy in the 'remote' and 'local' conditions did not differ significantly, nor did the use of flexible learning strategies coincide with high accuracy.

In explaining the main finding that location learning altered as a function of distinctiveness of non-geometric features, it can be argued that the novelty and complexity of the boundary shapes prevented participants from processing them as single units. The shapes used in the present study are not habitually encountered in day-to-day navigation, and participants were not likely to have relevant schemas for them in their LTM. At the same time, the quantity of segments composing these shapes may have overloaded WM and prevented participants from rapidly acquiring relevant schemas (Sweller, 1988; 1994). Instead, it is plausible that each boundary was processed as multiple discrete segments, and target location was in most cases referenced to one of these segments (yellow wall), as opposed to the overall geometric shape of the boundary. Indeed, this is confirmed by the fact that none of the participants reported using overall boundary shape to learn locations throughout the experiment. In fact, the majority of the participants declared using the yellow wall or a combination of features to reference the target location. In the 'local' and 'remote' conditions such discrete segments could be easily identified. In the 'geometry' condition more cognitive resources had to be used to identify relevant segments, which potentially reduced accuracy (Kalyuga et al., 1999). If a 'geometric module' did exist and there were qualitatively different rules for instantaneous processing of spatial geometry, these factors (i.e. complexity and novelty of the shapes) should not have impacted the accuracy of location learning across the three conditions. Thus from the above findings it can be tentatively argued that in the present case boundary cues did not take precedence.

Considering alternative explanations, the variances in accuracy between conditions could not be attributed to participants' individual differences, as by experimental design each participant took part in

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all conditions. There was also no relationship between trial order and accuracy, and thus, fatigue or practice-related improvements do not explain the results.

Therefore, the experimental data produced here offers some general support for the application of Cognitive Load Theory (Sweller, 1988; 1994) to boundary-learning, whilst disputing the notion of differential learning mechanisms (Doeller & Burgess, 2008) and the existence of a 'geometric module' (Cheng, 1986; Wang & Spelke, 2003; Chiandetti & Vallortigara, 2008). Although the 'geometric module' concept provides an interpretation for findings of some studies (Cheng, 1986; Benhamou & Poucet, 1998; Pearce et al., 2001; Wang & Spelke, 2003; Cheng & Newcombe, 2005; Chiandetti & Vallortigara, 2008; Doeller & Burgess, 2008; Lee & Spelke, 2010; Lee et al., 2013), it has received a significant challenge from substantial volume of other research (Gouteux et al., 2001; Learmonth et al., 2002; Cheng & Newcombe, 2005; Gray et al., 2005; Graham et al., 2006; Pearce et al., 2006; Cheng, 2008; Lew, 2011; Sturz et al., 2012; Zhou & Mou, 2016), in tandem with the present study. The learning principles described by Cognitive Load Theory, however, align with the pattern of findings in the current paper and offer an explanation for the overarching disparity in boundary-learning research. More specifically, participants were observed to disregard landmark cues in the experiments that employed simple and familiar boundary shapes (Cheng, 1986; Benhamou & Poucet, 1998; Pearce et al., 2001; Wang & Spelke, 2003; Cheng & Newcombe, 2005; Chiandetti & Vallortigara, 2008; Doeller & Burgess, 2008; Lee & Spelke, 2010; Lee et al., 2013; Redhead et al., 2013); but in the trials that used novel and relatively complex boundary shapes, boundary and landmark cues were noted to be in competition for attentional resources (Gray et al., 2005; Pearce et al., 2006; Redhead et al., 2013). The present research is consistent with the latter group of studies.

This study puts forward evidence to propose that cognitive processing capacity (as evidenced by poorer performance in the 'geometry' condition as compared to the 'local' or 'remote') plays a significant role in the prioritisation of spatial cues; and that spatial processing mechanism is not modular (i.e. unique in the case of boundary-learning). Further research needs to directly compare the mechanisms of learning locations in reference to simple/familiar and to complex/novel boundary shapes. It is also necessary to systematically define any additional factors influencing the distribution of attentional resources during boundary-learning.

The second aim of this study was to explore the effect of cue proximity on boundary-learning. The lack of significant differences between the 'local' and 'remote' conditions suggests that proximity of salient boundary segments does not influence the accuracy of boundary-learning. This is inconsistent with accounts from Tarmizi and Sweller (1988) and Sweller et al. (1990), and would need to be examined in more detail. A final supplementary purpose of the study was to investigate the impact of conscious learning strategies on accuracy. This was with respect to the observation of Kato and

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Takeuchi (2003), suggesting that people who consciously use flexible spatial learning strategies are better at learning locations. Contrary to the predictions, however, there was no effect of participants' conscious learning strategies on performance. In the context of the given experimental design (complex boundary shape and a single learning trial for each location), this suggests that conscious boundary-learning strategy does not influence accuracy after a brief learning session.

Limitations

Some limitations of the present study need to be acknowledged. First and foremost, data from a relatively small pool of participants was used, and the drop-out rate was high. Additionally, as the experiment was conducted remotely, compliance with experimental instructions could not be supervised.

Conclusion

In summary, the present study in combination with findings from other research yields support for the application of Cognitive Load Theory (Sweller, 1988; 1994) in characterising boundary-learning mechanism. The findings dispute the existence of a 'geometric module' (Cheng, 1986; Wang & Spelke, 2003; Chiandetti & Vallortigara, 2008), indicating that when the boundary shape is complex and unfamiliar, locations are learned in reference to a discrete segment of the boundary rather than its overall shape. It is argued that such a learning mechanism is more parsimonious, serving to minimise cognitive load. This research therefore potentially paves the way for further examination of boundary-learning mechanism in the context of Cognitive Load Theory.

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Appendix 1. Instructions

Exhibit 1: Instructions given prior to starting the experiment

Thank you for agreeing to take part in this study.

Please create your unique participant code by combining the last three letters of your surname with the last three digits of your phone number. You will be able to use this code, should you wish to withdraw from the study during the two weeks after conclusion of your participation.

Participant code:

To take part in this experiment you will require a quiet workspace, equipped with a computer, a desk and a chair. You will also need access to the internet.

Please ensure that you will not be disturbed during the next 40-50 minutes. Set up your workstation in accordance with the display screen equipment standards and adjust your monitor. If you have prescription glasses or contact lenses, please wear them during the experiment.

The experiment comprises of 18 trial sets. In each set you will first view a short video of navigation in a 3D virtual environment. Please observe the environment as you navigate and note the location of the white ball. However, do not write anything down. You may view this 'learning' video only once. Please ensure that you watch it until the end.

Then you will be presented with a second ('test') video of navigation in the same environment, but with the white ball absent from the scene. Your starting position and orientation within the environment will vary between the 'learning' and 'test' videos. Also direction of the light and position of the shadow may be altered. In the second video each corner of the navigational arena will be marked with a letter (i.e. A, B, C). Please identify the corner, in which the white ball was previously located and remember the corresponding letter. You may view the 'test' video multiple times. Once you are ready, press 'next' and type the letter in the appropriate field.

You will also have an option to submit any related comments, should you wish to do so. Your perception of the virtual navigational environment is the focus of this study. Although sharing comments and observations after each set of videos is optional, this will be greatly appreciated and may help with the interpretation of your performance on these tasks.

Halfway through the experiment (after 9 trial sets) you will be given 5 minutes to rest.

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Upon completion of all the trial sets you will be asked a couple of questions about the task and your demographic characteristics. There will also be an opportunity to give feedback on your participation in this research.

You will be given an opportunity to practice the task, as you will view two practice trial sets before beginning the experiment properly.

Once you are ready, please press the 'next' button to begin your practice.

Exhibit 2: Instructions given immediately prior to practice trials

Please find a quiet workspace and ensure that you will not be disturbed during the next 40-50 minutes. Set up your workstation in accordance with the display screen equipment standards [http://www.hse.gov.uk/pubns/ck1.pdf] and adjust your monitor. If you have prescription glasses or contact lenses, please wear them during the experiment.

Exhibit 3: Instructions given for learning videos

You will now be presented with a short video. Simply observe the environment as you navigate and note the location of the white ball. You can view the video only once.

Please ignore the adverts that appear once the video finishes and press the 'next' button once the video has finished playing.

Exhibit 4: Instructions given for test videos

You will now be presented with the second video of navigation in the same environment. Please be aware that the starting position and orientation will change in this video. Each corner of the navigational arena will be marked with a letter (i.e. A, B, C, D, E). Please identify the corner in which the white ball was previously positioned and remember the corresponding letter. You may view this video multiple times.

Please ignore the adverts that appear once the video finishes and press the 'next' button once the video has finished playing.

Exhibit 5: Instructions given for the 5-minute break

You have completed the first half of the experiment. Please take 5 minutes to rest away from the computer. Once 5 minutes elapse, please return to the computer and press 'continue'.

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Appendix 2. Questions

Exhibit 1: Questions asked at the end of each trial

Please answer the following question.

In which corner was the white ball located in the first video?

A
B
C
D
E

If you have any comments on how you were able to remember the location/how confident you are in your answer/or any other observations that you would like to share, please write them in the box below. Commenting is optional, but will be greatly appreciated. This may help to interpret your performance on this task. *[followed by free-text field]*

Exhibit 2: Questions asked at the end of the experiment

Thank you for completing the experimental part of the study. There are just a couple of questions left.

How did you remember the location of the white ball throughout the experiment? (you can only select one of the below or enter your own comments)

- I remembered where the white ball was placed within the overall shape of the arena
- I remembered where the white ball was placed in reference to a feature of the arena, which was immediately next to the white ball
- I remembered where the white ball was placed in reference to one (several) feature(s) of the arena, which was(were) not next to the white ball
- Other (please comment)

Give a detailed description of how you remembered the location of the white ball throughout the experiment. Did you change your strategy from trial to trial and in what way? Which cues in the environment were most helpful, if any? What made it hard to remember the location? Also please mention if your participation in the experiment was at any point disrupted or disturbed. *[followed by free-text field]*

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Please provide the following demographic information.

Gender: Male / Female

Age:

I will be grateful if you could give feedback on your participation in this research. Your feedback will be taken into consideration for the design of future experiments. *[followed by free-text field]*